Unlocking real-world turbine performance:
What nacelle-mounted lidar can teach us

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Photo: ZX Lidars

Wind turbine performance has traditionally been evaluated using nacelle anemometry: a single measurement height, limited inflow characterization, and a reliance on assumptions about the atmospheric conditions and flow effects across the rotor plane and nacelle. But as the industry seeks to better understand the impact of complex terrain and flow conditions on turbine performance, better tools are emerging to close the gap between idealized and real-world turbine behaviour.

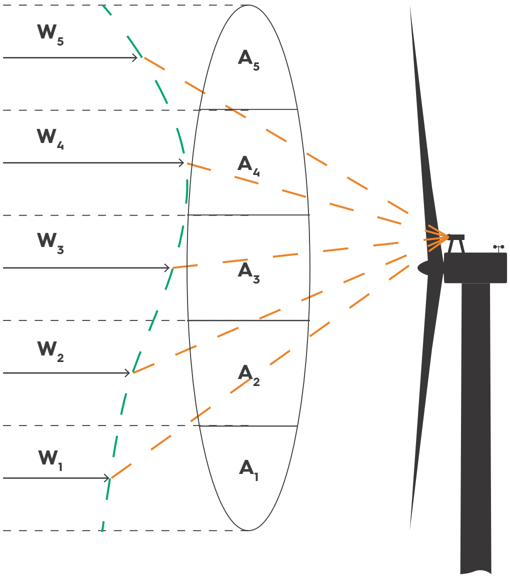
Nacelle-mounted lidar is one of those tools. By measuring inflow characteristics across the entire rotor plane, it provides a richer and more detailed picture of real-world turbine operating conditions. This article summarizes a recent analysis of a turbine using an **11-height, 6-range ZX nacelle lidar system**, revealing how veer, turbulence intensity (TI), and inflow structure meaningfully impact turbine performance.

From single-point measurements to full rotor insight

Traditional nacelle anemometers measure wind speed at a single point. By contrast, nacelle lidar captures wind speed, direction, veer, and TI across the full rotor disk — from **56m** to **195m** above hub height and up to **385m** upstream.

This enables calculation of **rotor equivalent wind speed (REWS)**, a more representative measure of the energy content in the incoming wind.

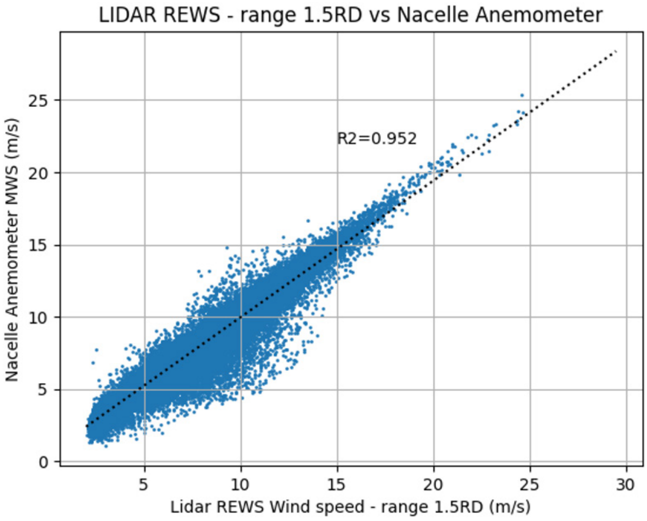
Photo: ZX Lidars



Nacelle-lidars measure flow across the whole rotor plane

REWS vs. nacelle anemometry: strong agreement

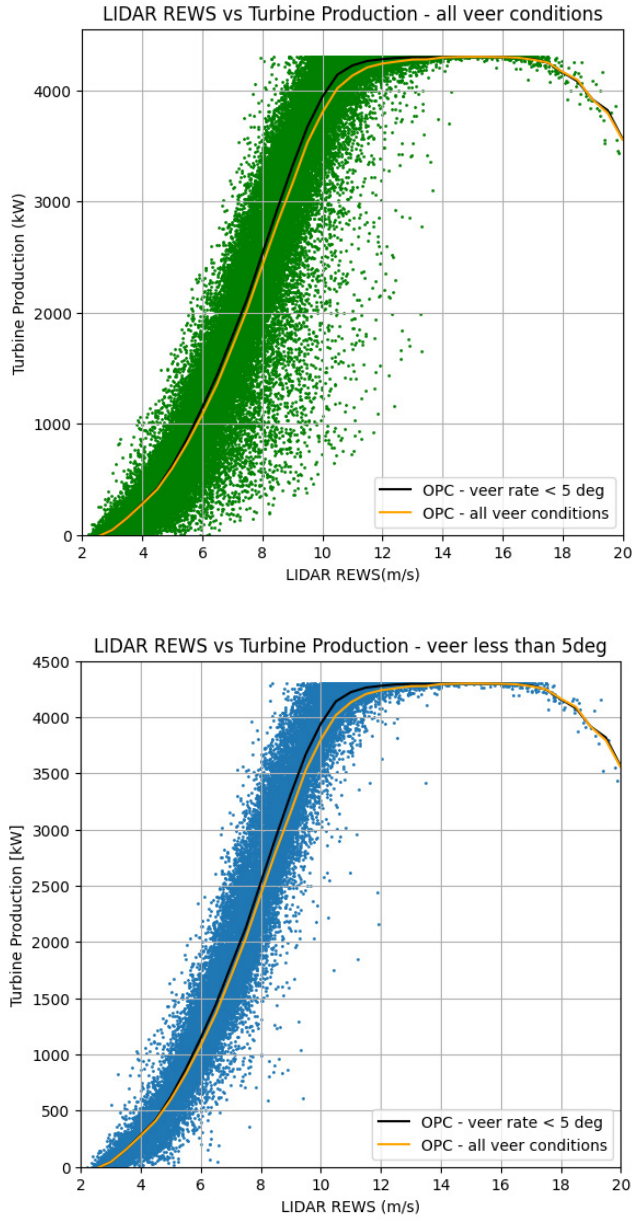
The study shows strong alignment between the lidar-derived REWS and the nacelle anemometer measurements, validating lidar's capability for inflow characterization.



Scatter plot of the lidar REWS and the nacelle-mounted anemometer at 1.5RD

Real-world performance: what's driving the scatter?

When plotting turbine output against either REWS or nacelle wind speed, the familiar "thick" scatter along the power curve showing non-ideal turbine behavior becomes immediately apparent.



Scatter plots of turbine production versus lidar rews and nacelle-mounted anemometer

This raises the question: **What atmospheric conditions are driving deviations from ideal performance?**

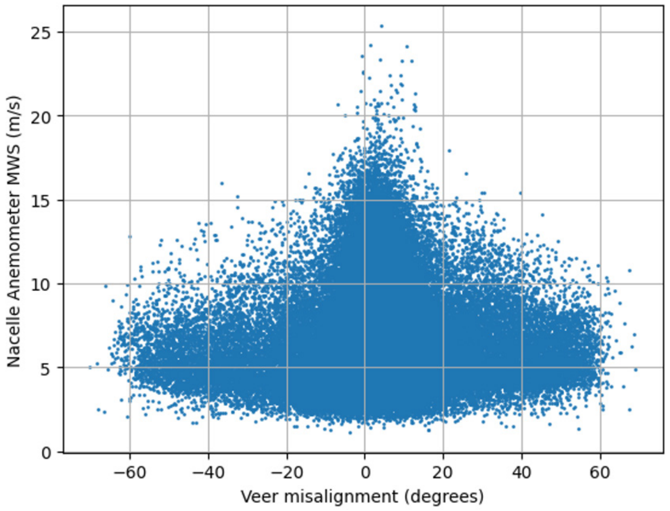
Two key contributors emerge from the analysis:

- **Wind veer** — the change in wind direction with height
- **Turbulence intensity (TI)** — the variability of wind speed over short time periods

Both significantly affect aerodynamics and turbine control responses.

How veer shapes turbine output

Lidar measurements show that **most veer is within ±10°**, but that large veer events occur most often **within the ramp region of the power curve**, where turbines are most sensitive to inflow alignment.

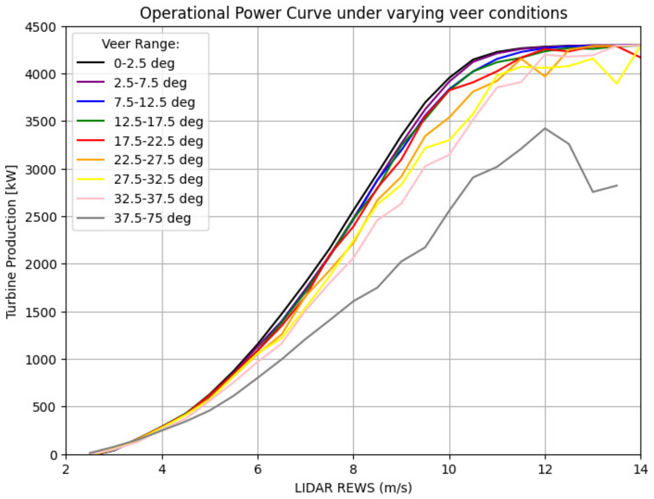


Nacelle-mounted lidar showing extent of veer misalignment

High veer = reduced energy capture?

Operational power curves filtered by veer demonstrate a clear pattern:

- Low veer → **higher output**
- Medium to high veer → **consistent underperformance** in line with the classic cosine-loss expectation



Measured power curves showing the dependence of turbine performance on veer

Weighted across typical wind speed distributions, the difference amounts to **3–4% more energy** during low-veer conditions (<10°) — a material impact.

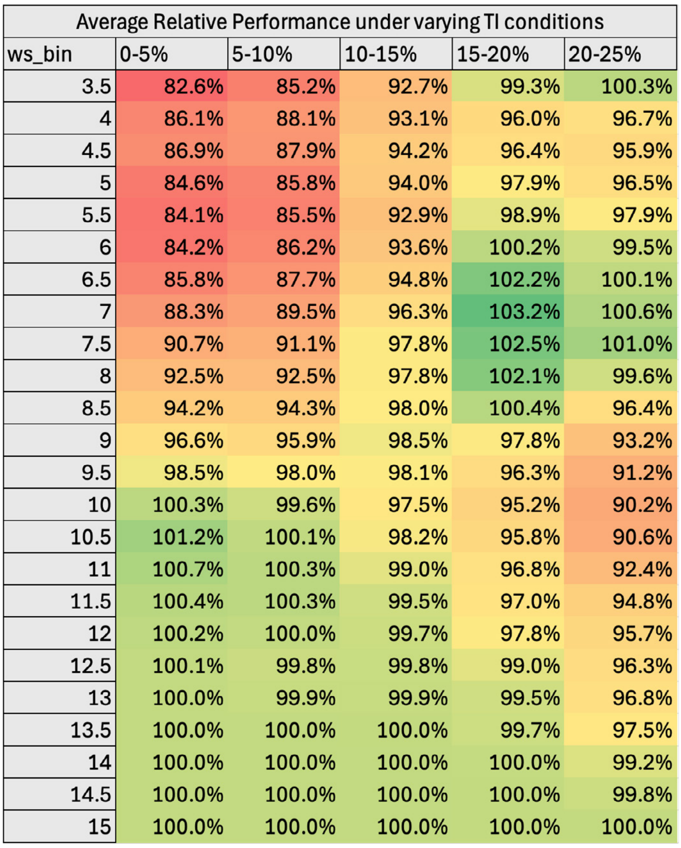
Turbulence intensity: another driver of performance

Turbulence intensity impacts both aerodynamic efficiency and control system behavior.

Low TI vs. high TI: different behaviors

Filtering performance by TI reveals two contrasting trends:

- ➜ **High TI** boosts performance in sub-rated power wind speeds (by sustaining energy in the flow)
- ➜ **High TI** reduces performance near the knee of the power curve (due to increased pitching and regulatory control actions)
- ➜ Conversely, **low TI** conditions underperform in the ramp but outperform near rated wind speed.



Average Relative Performance under varying TI conditions

ws_bin	0-5%	5-10%	10-15%	15-20%	20-25%
3.5	82.6%	85.2%	92.7%	99.3%	100.3%
4	86.1%	88.1%	93.1%	96.0%	96.7%
4.5	86.9%	87.9%	94.2%	96.4%	95.9%
5	84.6%	85.8%	94.0%	97.9%	96.5%
5.5	84.1%	85.5%	92.9%	98.9%	97.9%
6	84.2%	86.2%	93.6%	100.2%	99.5%
6.5	85.8%	87.7%	94.8%	102.2%	100.1%
7	88.3%	89.5%	96.3%	103.2%	100.6%
7.5	90.7%	91.1%	97.8%	102.5%	101.0%
8	92.5%	92.5%	97.8%	102.1%	99.6%
8.5	94.2%	94.3%	98.0%	100.4%	96.4%
9	96.6%	95.9%	98.5%	97.8%	93.2%
9.5	98.5%	98.0%	98.1%	96.3%	91.2%
10	100.3%	99.6%	97.5%	95.2%	90.2%
10.5	101.2%	100.1%	98.2%	95.8%	90.6%
11	100.7%	100.3%	99.0%	96.8%	92.4%
11.5	100.4%	100.3%	99.5%	97.0%	94.8%
12	100.2%	100.0%	99.7%	97.8%	95.7%
12.5	100.1%	99.8%	99.8%	99.0%	96.3%
13	100.0%	99.9%	99.9%	99.5%	96.8%
13.5	100.0%	100.0%	100.0%	99.7%	97.5%
14	100.0%	100.0%	100.0%	100.0%	99.2%
14.5	100.0%	100.0%	100.0%	100.0%	99.8%
15	100.0%	100.0%	100.0%	100.0%	100.0%

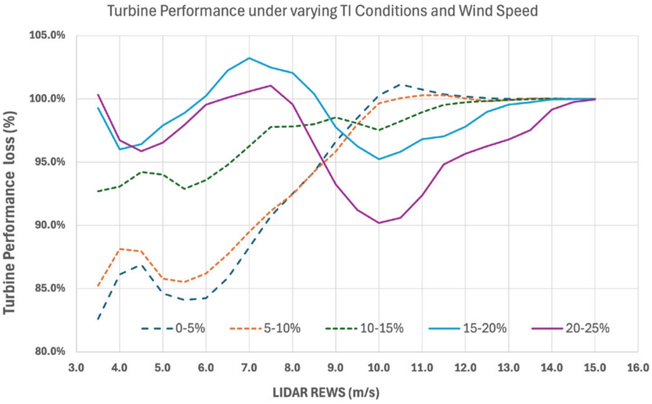
Impact of TI on relative performance across range of operational wind speeds (filtered for low veer conditions)

These patterns match expectations of many previous studies, notably those summarized in the various proceedings of the Power Curve Working Group (PCWG) but are more significant in low-TI conditions of this study.

Combined effects: veer, TI, and wind speed interactions

When analyzing veer and TI together across wind speed bins, a clearer picture emerges:

- ➜ Performance losses due to veer are **most significant in mid-range wind speeds**
- ➜ TI dominates behavior in both low and high winds
- ➜ Inflow structure (wind veer, shear, turbulence, alignment) interacts non-linearly with turbine controls, shaping real-world performance far more than a simple power curve can show



Understanding these dynamics is essential for accurate performance assessment, lifetime energy modelling, and root-cause investigations.

Why this matters for wind farm owners & operators

Nacelle-mounted lidar unlocks capabilities that were previously inaccessible:

1. High-resolution performance diagnostics

Operators can identify when and why turbines underperform — isolating atmospheric drivers instead of relying on assumptions.

2. Informed OEM and control-scheme discussions

By quantifying veer and TI impacts, operators can gain better insight into how pitch, yaw, and derating algorithms respond to real inflow conditions.

3. Better energy modeling & forecasting

REWS-based analysis aligns more closely with physical inflow characteristics, improving uncertainty estimates in annual energy production (AEP) projections.

4. Wake-aware operations

Wake effects dramatically influence veer and TI distributions; lidar provides the upstream visibility needed to measure those impacts directly.

Next steps: the future of lidar-enabled performance analytics

While this analysis offers compelling insights, it is still based on **a single turbine at a single site**. Scaling studies across turbine types, sites, terrains, and atmospheric regimes is the logical next step.

Key questions remain:

- How do wake effects influence observed veer dynamics?
- Can OEM control systems be optimized for high-veer or high-TI conditions?
- What is the best way to correct lidar measurements in highly dynamic inflow?
- Are the veer/TI impacts seen here more universally applicable?

The answers will shape the next generation of performance standards and operational strategies.

Conclusion: the use of lidar is changing how we understand wind turbine performance

This study confirms that nacelle-mounted lidar is not merely a replacement for nacelle anemometry — it is a tool that helps to unlock a deeper understanding of turbine aerodynamics and atmospheric interactions.

By quantifying veer, turbulence intensity, and inflow structure across the entire rotor plane, operators can move beyond "textbook" performance curves and begin to evaluate true turbine behavior under real atmospheric conditions.

As the industry deploys more lidar systems and more of these types of analysis are carried out, we can expect significant improvements in performance analytics, operational efficiency, and ultimately, energy yield.

Photo: ZX Lidars

If you have any queries related to the content of this paper, please contact:

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